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Best Evidence Science Teaching: research evidence in action

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Abstract
'Best Evidence Science Teaching' (BEST) is a collection of open-access, research-evidence-informed resources for science teaching at 11–14. BEST includes progression toolkits comprising sequenced learning steps, diagnostic questions and response activities. Case studies illustrate how teachers are using BEST resources. Observations and interview data from 12 teachers suggest that BEST allowed these teachers to develop their practice in the following key areas identified by the Education Endowment Foundation (EEF) *Improving Secondary Science* guidance report: preconceptions, memory, metacognitive talk, feedback, practical work and language of science. Findings suggest that research-evidence summaries were being used by teachers to inform how they describe and explain scientific concepts, listen to student responses, sequence teaching and select models and analogies. As such, they provided access to no-cost, subject-specific professional development 'just in time' for teaching.

Transforming research evidence into teaching practice

The push of current education policy is to encourage schools and teachers to participate in trials and engage with research (Cabinet Office, 2018; The Royal Society and British Academy, 2018), yet research is often inaccessible to teachers. Coldwell *et al* (2017) found limited evidence of teachers using research findings to change their practice. As Black and Wiliam (1998: 16–17) highlight:

'Teachers will not take up attractive sounding ideas, albeit based on extensive research, if these are presented as general principles which leave entirely to them the ask of translating them into everyday practice – their classroom lives are too busy and too fragile for this to be possible for all'.

Studies have suggested that research-informed diagnostic materials can enable teachers to identify teaching and learning needs, support non-specialist teachers and have a positive impact on student learning (Millar, Leach & Osborne, 2006). A key challenge for science educators is to transform research evidence into resources and pedagogical approaches that are accessible to teachers. This article reports on one response to this challenge, the Best Evidence Science Teaching (BEST) project.

BEST (www.stem.org.uk/best-evidence-science-teaching) is a collection of open-access resources comprising the following, designed to enable teachers to use and gather evidence in the classroom:

- learning progression pathways, which exemplify how understanding of 15 big ideas (listed in Table 1) in science education can be developed through appropriately sequenced key concepts;
- diagnostic questions, which use research on children's ideas to inform the question and responses, with the distractors (incorrect answers) informed by research into children's ideas in science (for example, Driver, 1985);
- response activities, to promote purposeful practical work, metacognition and progression in conceptual understanding.

A 'progression toolkit' is provided for each key concept, consisting of sequenced learning steps, diagnostic questions and response activities. These draw upon the Evidence-based Practice in Science Education (EPSE) project (Millar *et al*, 2002), which used diagnostic assessment to enhance learning by monitoring students' understanding of scientific ideas.

This article first outlines the principles behind the design of the BEST resources (formative and diagnostic assessment) and then reports on observations of how teachers used the resources with students in the 11–14 age range.

Table 1. Big ideas for which BEST offers research-informed resources.

Biology	Chemistry & Earth Science	Physics
❍ The cellular basis of life	❍ Substances and properties	❍ Matter
❍ Heredity and life cycles	❍ Particles and structure	❍ Forces and motion
❍ Organisms & their environments	❍ Chemical reactions	❍ Sound, light and waves
❍ Variation, adaptation & evolution	❍ Earth's atmosphere	❍ Electricity and magnetism
❍ Health and disease	❍ Dynamic earth	❍ Earth in space

Formative and diagnostic assessment: why it is important and how it can be done

Formative assessment is used in different ways in the science education literature. In the BEST project, formative is used to describe the function of assessment evidence, rather than the assessment itself:

'An assessment functions formatively to the extent that evidence about student achievement is elicited, interpreted, and used by teachers, learners or their peers to make decisions about the next steps in instruction that are likely to be better, or better founded, than the decisions they would have made in the absence of that evidence' (Wiliam, 2018: 48).

Assessment only becomes formative when the evidence collected is used by the teacher to adapt to meet the needs of students (Black & Wiliam, 1998: 2). Cowie, Harrison and Willis (2018) describe the importance of 'noticing' – a responsive act that invites action in response to evidence of student ideas in the moment – in the formative assessment process. Substantial knowledge and skill for effective use of formative assessment is needed by teachers (Bennett, 2003: 20), yet little time and few resources are currently available to support teachers in the development of formative practices.

BEST resources supporting formative assessment

One method of supporting formative assessment practices is the use of diagnostic items to find out what students understand about scientific ideas. The BEST resources offer a range of diagnostic formats including:

- simple and two-tier multiple-choice questions;
- talking heads;
- confidence grids;
- explanation stories.

These are designed to enable teachers to check prior knowledge and understanding, and to reveal common preconceptions and misunderstandings of science ideas. This allows the teacher to identify what they need to do next to promote learning.

The learning progression toolkits are designed to help teachers respond to the 'what's next' question in terms of developing students' understanding of key concepts in physics, chemistry, earth science and biology, demonstrating possible next steps based on approaches reported in research literature.

Reading age (measured using the Flesch–Kincaid grade level readability test, which is available as a tool in *Microsoft Word*) has been deliberately kept below the age of students in order to maximise

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comprehension, and the resources are editable to allow teachers to adapt to their own context.

In this study, the aim was to find out how teachers were using BEST resources and whether access to the research-informed resources led to changes in teaching practice. Below, we outline the method used to find out how they were being used by teachers.

BEST in action: method

A case study approach was used to explore how teachers use the Best Evidence Science Teaching resources. The case studies were based on semi-structured interviews and observations of teachers in ten schools local to the research team, invited to participate because they had recently attended professional development about the BEST resources.

At the time of the study, the science education community was giving a lot of attention to the Education Endowment Foundation (EEF) *Improving Secondary Science* guidance report (EEF, 2018), which made seven recommendations for improving secondary science. Although the basis for including each of the seven recommendations – and excluding others – is unclear, the recommendations included cover a broad range of areas that are relevant to science teaching, so an observation tool was derived from the EEF guidance report and was used, along with a combination of structured and unstructured narrative observations, to identify evidence of where the BEST resources supported teachers to:

- build on ideas that students bring to lessons (preconceptions);
- promote self-regulation (students directing their own learning);
- use modelling to support understanding;
- support students to remember;
- use practical work purposively; develop scientific vocabulary, reading and writing;
- use structured feedback to help students to learn.

As a qualitative study, we do not aim for generalisability. Rather, we describe the range of ways in which we observed teachers using the BEST resources, which might be relatable to teachers in other contexts working towards similar aims.

The study involved 12 teachers in the north of England. Nine teachers were observed using BEST resources in science lessons and were then interviewed; three teachers provided detailed accounts of their experiences. Of the 12 teachers, two worked in the independent sector and the remaining 10 worked in the state-maintained sector. All teachers had participated in an instance of professional development led by the BEST curriculum development team and taught students in the 11–14 age range, not always within their specialism. Teachers varied in number of years' experience (from one PGCE student to a teacher with 23 years' experience) and in their specialism, with physics, chemistry and biology teachers represented in the sample, although no chemistry BEST items were observed in this study. All teachers are given pseudonyms below. Ethical approval was obtained from the relevant university departmental ethics committee, and voluntary informed consent was obtained from participating teachers to participate in observations and interviews.

All resources were open access and teachers were able to use them 'just in time' to inform forthcoming teaching.

Findings

Teachers in the study used the BEST resources with the 11–14 age group in different ways. In terms of planning, some teachers reported using the teachers' notes (which include short summaries of relevant research literature) and noted changes to how they:

1. describe key scientific concepts (e.g. energy, friction) in response to evidence presented in the notes;
2. sequence teaching (e.g. of light and sound);

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3. select appropriate analogies and models to avoid creating or reinforcing misunderstandings (e.g. avoiding describing the nucleus as 'the brain of the cell').

These teachers reported that they were more attuned to students' responses after reading the teachers' notes.

In lessons, a range of diagnostic and response items were observed in action in a number of ways. For some, diagnostic items were used to look at progress within a lesson or over a sequence of lessons. For others, their focus was on responding to students' ideas within the lesson and using students' ideas to inform teaching – that is, using the resources formatively. Where this happened, teachers made use of individual 'think time', paired and group talk, and whole-class responses.

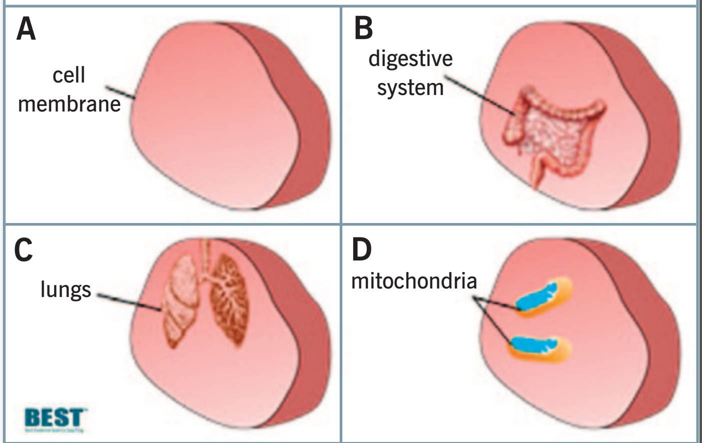
Examples drawn from the case studies are presented below, organised under the six themes observed in the study: preconceptions, memory, practical work, language of science, feedback and metacognition. The examples demonstrate a range of ways of using the resources formatively and responsively, as intended.

Preconceptions: building on the ideas that students bring to lessons

Understanding the ideas that students bring to science lessons and developing thinking through cognitive conflict and discussion is a key feature of the diagnostic items. All teachers were observed using diagnostic items. One example was Miranda, who used a simple multiple-choice diagnostic question: 'Organ or organelle?' (Figure 1). The evidence on which this item is based is found in Box 1.

Miranda projected the question onto the white board, telling the class that *'each drawing shows a single cell'*, and a show of hands was used to collect responses for each option. For question 1,

Organ or organelle



Which drawing shows the structure that...

1 ...lets the cell take in oxygen?
2 ...lets the cell take in food and other nutrients?
3 ...lets the cell take in energy from food?
4 ...lets the cell gets rid of waste?

Figure 1. Diagnostic item 'Organ or organelle?' (multiple choice).

Box 1: Evidence base for diagnostic item 'Organ or organelle?'

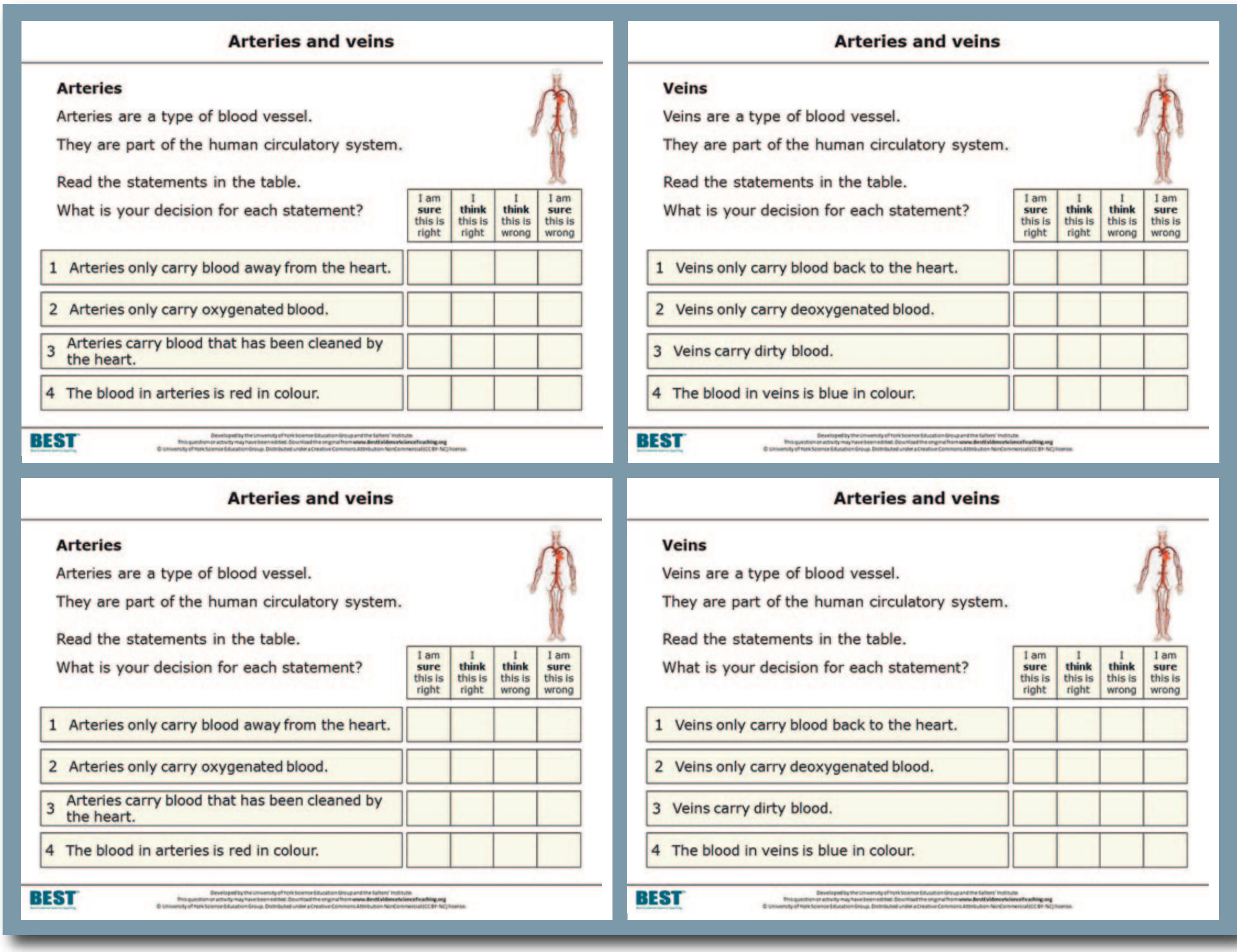
This item was developed from misunderstandings reported in the research literature. Dreyfus and Jungwirth (1988) found that many 16-year-olds struggled to explain how cells carry out life processes. Many of the students thought that cells contain macroscopic organs such as a digestive tract (e.g. for nutrition) or lungs (e.g. for respiration).

most students selected 'C'. Miranda was then able to identify what students understood about cell and organ size and scale, which she dealt with using whole-class teaching to build on ideas elicited from students, asking them to feel lungs in their body and to think about how they see cells (under a microscope). In addition to teaching size and scale, she was able to identify faulty reasoning:

Student (responding to reasons for answering C): *'Lungs have cells.'*

Teacher: *'Yes, lungs have cells, but do cells have lungs?'*

The use of the item allowed Miranda to understand the ideas that students were bringing to the lesson, to develop their thinking through cognitive conflict, supported by whole-class question and response connected to their bodies and what they had previously learnt.



Arteries and veins

Arteries

Arteries are a type of blood vessel.

They are part of the human circulatory system.

Read the statements in the table.

What is your decision for each statement?

	I am sure this is right	I think this is right	I think this is wrong	I am sure this is wrong
1 Arteries only carry blood away from the heart.				
2 Arteries only carry oxygenated blood.				
3 Arteries carry blood that has been cleaned by the heart.				
4 The blood in arteries is red in colour.				

BEST

Arteries and veins

Veins

Veins are a type of blood vessel.

They are part of the human circulatory system.

Read the statements in the table.

What is your decision for each statement?

	I am sure this is right	I think this is right	I think this is wrong	I am sure this is wrong
1 Veins only carry blood back to the heart.				
2 Veins only carry deoxygenated blood.				
3 Veins carry dirty blood.				
4 The blood in veins is blue in colour.				

BEST

Arteries and veins

Arteries

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BEST

Arteries and veins

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They are part of the human circulatory system.

Read the statements in the table.

What is your decision for each statement?

	I am sure this is right	I think this is right	I think this is wrong	I am sure this is wrong
1 Veins only carry blood back to the heart.				
2 Veins only carry deoxygenated blood.				
3 Veins carry dirty blood.				
4 The blood in veins is blue in colour.				

BEST

Figure 2. Diagnostic items 'Arteries and veins' and 'Circulation' (confidence grids).

Box 2: Evidence base for 'Arteries and veins' and 'Circulation'.

This item was developed from misunderstandings reported in the research literature, such as that the heart filters or cleans the blood, that arteries carry 'clean' blood while veins carry 'dirty' blood, that arteries only carry oxygenated blood, while veins only carry deoxygenated blood, and that deoxygenated/venous blood is blue in colour (Arnaudin & Mintzes, 1985; Bartoszeck, Machado & Amann-Gainotti, 2011; Özgür, 2013: Schoon & Boone, 1998).

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Memory: supporting students to retain and retrieve knowledge

Julie had previously taught the human circulatory system and used four confidence grids (Figure 2).

She then used the same confidence grids in an introductory lesson on plant transport including the structure and function of the xylem and phloem. Julie wanted students to remember what they had been taught about circulation in humans and to link their knowledge to their interpretation of a demonstration of plant transport using red food colouring and celery. Julie's use of the BEST resources focused on reviewing material taught previously and elaborating by making connections between circulation in animals and in plants. Once key ideas had been revised, she collected individual responses to the confidence grid on paper in order to compare with their responses provided during the previous topic of animal circulation.

Julie used the resources to help students not only to make connections between transport in plants and animals but also to look for whether or not there had been progress in their understanding from the lesson on human circulation to the lesson on plant circulation. Julie reported that she intended to look at and use the students' responses to inform the next lesson and to identify any revision that would be necessary.

Practical work – using practical work purposefully and as part of a learning sequence

Camilla used diagnostic and response items to introduce the year 9 (ages 13–14) energy topic. Following the item 'Types of energy store' (Figure 3), Camilla used heavily scaffolded discussion with students to identify what they had remembered and understood from the previous lesson on energy sources. The evidence on which this item is based is presented in Box 3.

Camilla was able to identify difficulties that students had with both identifying energy stores and using scientific language to describe the transfer of energy to different stores. Camilla then used the response item 'Circus of energy stores' (Figure 4) to give students practice in thinking and talking about energy stores. In doing so, her approach to practical work was not only hands on but 'minds-on', as she had a clear focus in promoting their learning in relation to identifying and describing energy stores and energy transfers. During the practical, students were able to discuss their ideas with each other and Camilla was able to interact with individual groups to help them to develop their thinking and the expression of their ideas.

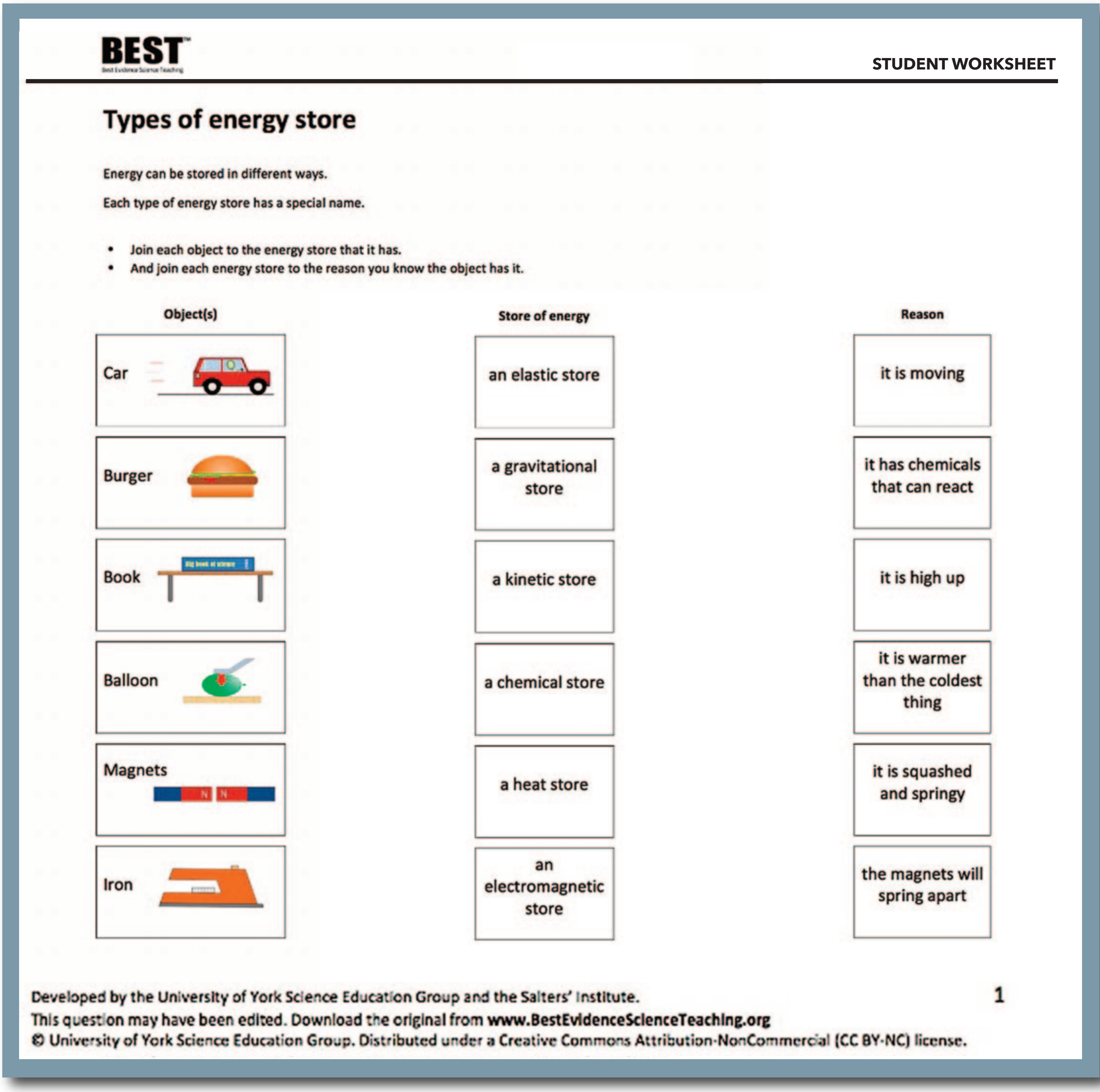
This practical session with use of both diagnostic and response items allowed Camilla to identify students' difficulty with the precise use of language necessary to communicate scientific ideas about energy. Recognition of this through the diagnostic tool meant that Camilla's conversations with students throughout the lesson were focused on building precision and the correct use of language. The teacher continually checked understanding of vocabulary related to the concept of energy and energy transfer.

Language: developing scientific vocabulary and supporting students to read and write about science

Frazer used BEST 'talking head' item 'Making friction' (Figure 5 on page XX) with a year 8 class (ages 12–13). The evidence on which this item is based is found in Box 4. He used it at the start and end of a lesson after showing a short video of a bus sliding on ice. The item revealed that no students could identify the correct explanation for what causes friction between two bodies.

In a post-lesson interview, Frazer reported that students' responses to the talking head item had influenced his teaching because he knew from their responses that allowing discussion would not have allowed them to develop the scientific understanding of friction.

⟶ p.30



BEST

STUDENT WORKSHEET

Types of energy store

Energy can be stored in different ways.

Each type of energy store has a special name.

- Join each object to the energy store that it has.
- And join each energy store to the reason you know the object has it.

Object(s)	Store of energy	Reason
Car	an elastic store	it is moving
Burger	a gravitational store	it has chemicals that can react
Book	a kinetic store	it is high up
Balloon	a chemical store	it is warmer than the coldest thing
Magnets	a heat store	it is squashed and springy
Iron	an electromagnetic store	the magnets will spring apart

Developed by the University of York Science Education Group and the Salters' Institute. 1

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Figure 3. Diagnostic item 'Types of energy store' (linking ideas).

Box 3: Evidence base for 'Types of energy store'.

This item was developed based on approaches to teaching energy using a model of 'energy stores' and 'energy pathways' as described by, for example, Boohan (2014), Millar (2014) and Tracy (2014).

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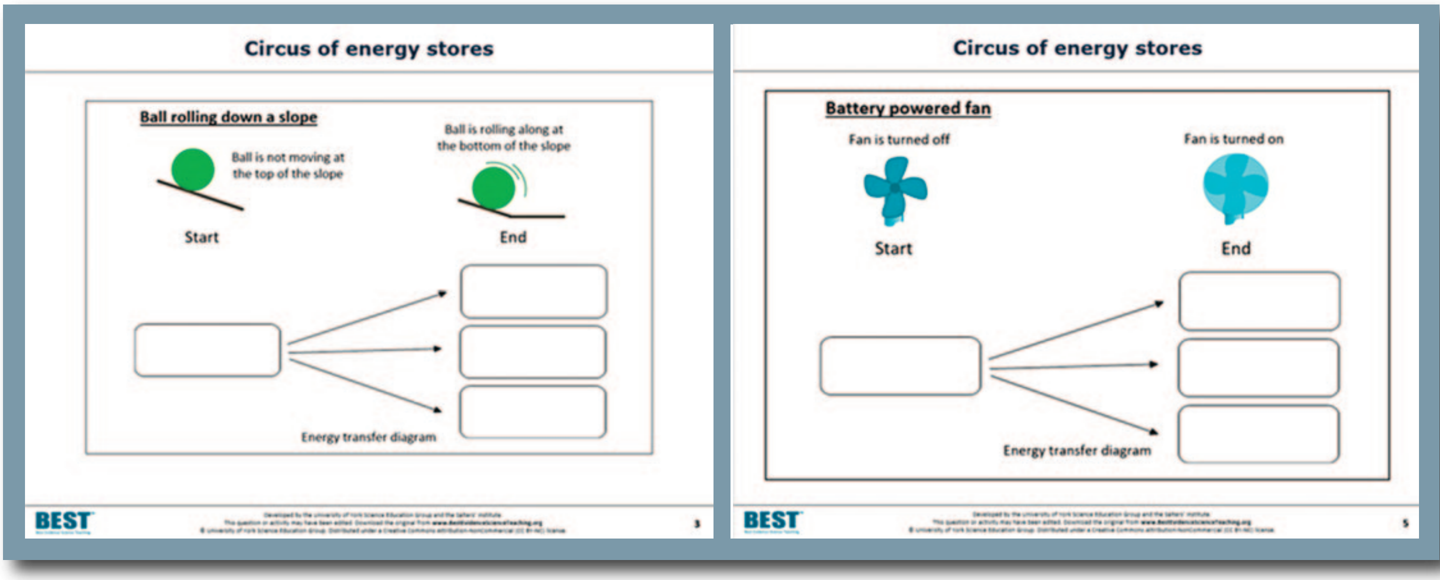

Figure 4. Extracts from 'Circus of energy stores' response item.

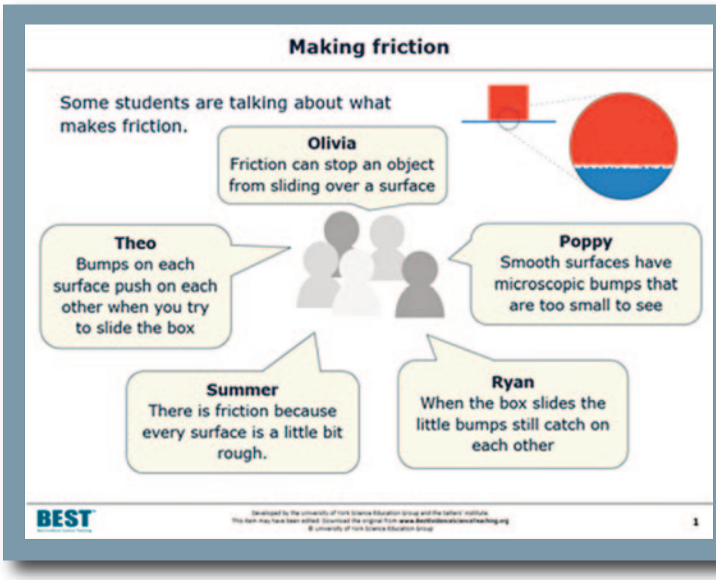

Figure 5. Diagnostic item 'Making friction' (talking heads, multiple choice).

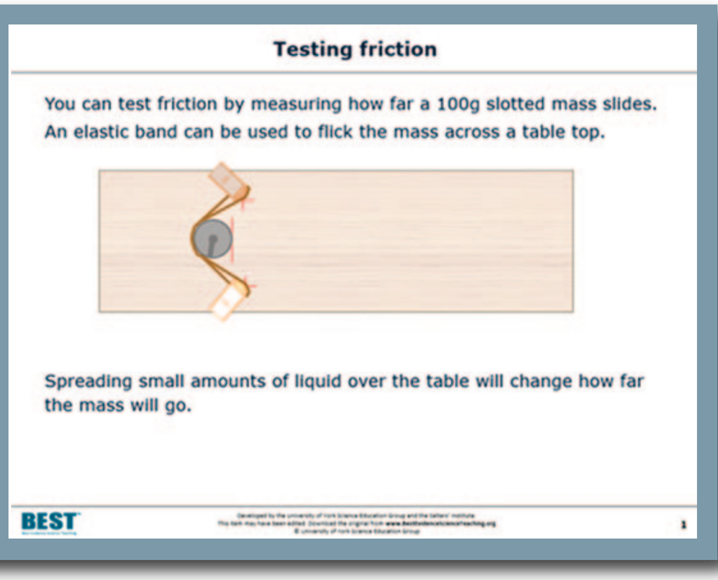

Figure 6. Response activity 'Testing friction' (predict–explain–observe–explain).

Box 4: Evidence base for 'Making friction'.

This item was developed from misunderstandings reported in the research literature, such as not identifying friction as a force (perhaps because it is generated by – rather than causes – an interaction between objects), thinking that friction does not act between objects that are not moving, and thinking that friction is directionless (as distinct from a force that opposes motion) (Stead & Osborne, 1980, 1981; Hart, 2002).

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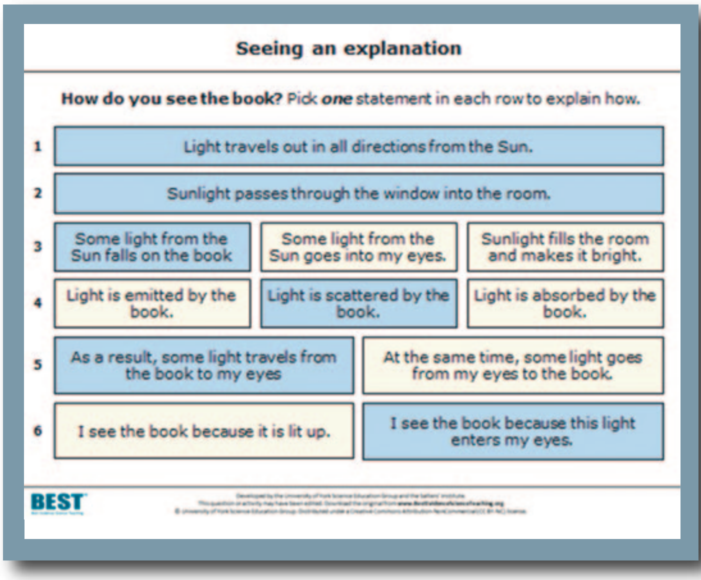

Seeing an explanation

How do you see the book? Pick *one* statement in each row to explain how.

1	Light travels out in all directions from the Sun.		
2	Sunlight passes through the window into the room.		
3	Some light from the Sun falls on the book	Some light from the Sun goes into my eyes.	Sunlight fills the room and makes it bright.
4	Light is emitted by the book.	Light is scattered by the book.	Light is absorbed by the book.
5	As a result, some light travels from the book to my eyes	At the same time, some light goes from my eyes to the book.	
6	I see the book because it is lit up.	I see the book because this light enters my eyes.	

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Figure 7. Diagnostic item 'Seeing an explanation' (explanation story multiple choice).

Box 5: Evidence base for 'Testing friction'.

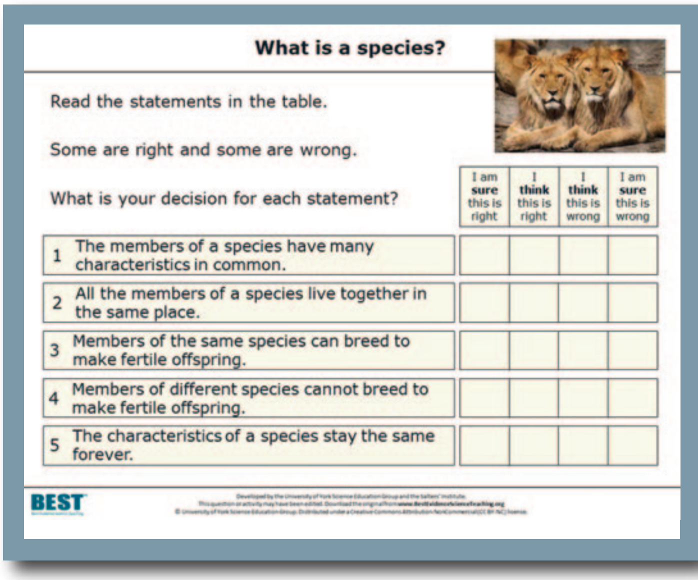
This item was developed from misunderstandings reported in the research literature about how we see, such as the non-explanation that 'light helps us to see' or that rays travel from the eye to the object (Andersson & Karrqvist, 1983; Guesne, 1985; Ramadas & Driver, 1989).

He therefore moved from the BEST item to a class practical comparing friction on different surfaces. Frazer returned to the talking heads item at the end of the lesson and was able to observe that more students were able to attribute friction to the 'bumpiness' of the surface. Frazer reported that the teacher notes had influenced the language he used to describe friction, moving from describing objects as having more or less friction to describing friction as a force preventing motion. He reported that this would be the starting point for the next lesson where he would use the item 'Testing friction' (Figure 6 on page XX), which extends the idea to look at friction as a force that slows things down.

Similarly, Jasmine used an explanation story multiple-choice item (Figure 7) with a year 8 class to support students to use vocabulary to accurately explain how you see a book. The evidence on which this item is based is found in Box 5. In points 3–6, students must engage with the text and make decisions about which is correct. This required comprehension of the statements and of the science of light.

Feedback: using structured feedback to move on students' thinking

Following a series of lessons on selective breeding, Ryan was moving on to species and extinction with a year 8 class. At the start of the lesson he gave



What is a species?

Read the statements in the table.

Some are right and some are wrong.

What is your decision for each statement?

		I am sure this is right	I think this is right	I think this is wrong	I am sure this is wrong
1	The members of a species have many characteristics in common.				
2	All the members of a species live together in the same place.				
3	Members of the same species can breed to make fertile offspring.				
4	Members of different species cannot breed to make fertile offspring.				
5	The characteristics of a species stay the same forever.				

BEST

Figure 8. Diagnostic item "What is a species?' (confidence grid).

Box 6: Evidence base for 'What is species?'

This item was developed from misunderstandings reported in the research literature, including that students often distinguish between species in overly simplistic ways – for example, based solely on visible differences or simply as a group of organisms that can breed to produce fertile offspring, without considering other factors (Chung, 2004; Jiménez-Tejada, Sánchez-Monsalve & González-García, 2013; Ellis & Wolf, 2010).

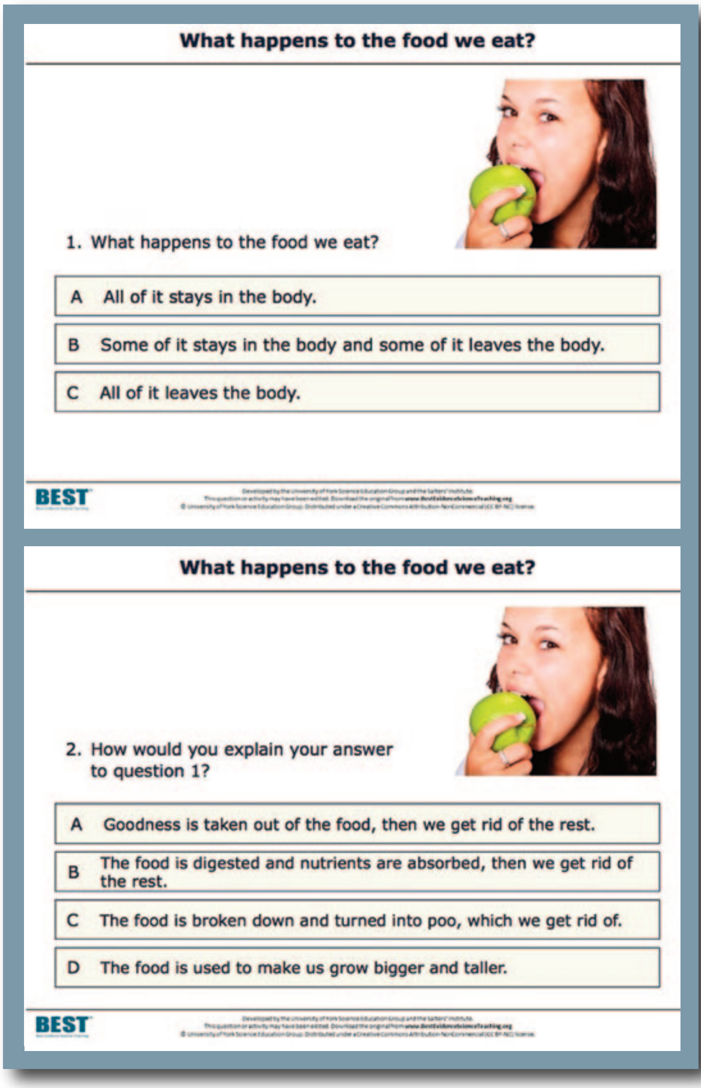


Figure 9. Diagnostic item ‘What happens to the food we eat?’ (two-tier multiple choice).

Box 7: Evidence base for ‘What happens to the food we eat’.

This item was developed from misunderstandings reported in the research literature about how we see, such as the non-explanation that ‘light helps us to see’ or that rays travel from the eye to the object (Andersson & Karrqvist, 1983; Guesne, 1985; Ramadas & Driver, 1989).

students a confidence grid to complete and discuss with a partner (Figure 8 on page XX). Box 6 presents the evidence base associated with this item.

During this time, Ryan circulated around the classroom discussing students’ answers with them and was able to gain understanding of their understanding of the species concept. A teaching session focused on the concept of species followed. Students were then asked to return to their confidence grids and again discuss with their partner whether they would now change any of their responses and to mark these with a green pen. Being able to review answers gave students the opportunity to monitor their learning. Ryan then asked them if they had changed any of their answers, what these were and why they had changed them. Further questions emerged from the students at this stage, such as *‘why can’t a mule reproduce?’*

Metacognitive talk and dialogue in the science classroom

‘What happens to the food we eat?’ (Figure 9) is based on research evidence presented in Box 7. Working with a year 7 group (ages 11–12), Heather printed the diagnostic item onto A3 paper and organised students into groups. She asked students to discuss their ideas and facilitated a whole-class discussion focused on the development of scientific explanations. Heather achieved this by asking questions such as *‘do you agree?’* and *‘why do you not agree?’* to better understand why students thought what they did. Heather then asked how the responses could be developed into better scientific explanations. Students offered suggestions such as replacing ‘goodness’ with ‘nutrients’, building on prior learning about what a nutrient is. This approach allowed students to deepen their understanding of what happens during digestion, as Heather was able to respond to their ideas in the moment.

Conclusions

The case studies demonstrate that teachers in this study were able to incorporate research evidence, via the BEST resources, into their planning and teaching as a result of using the BEST resources. The study is based on a small number of teacher

observations, but we believe that the findings from observations are relatable to others. The online resource bank continues to be updated to ensure coverage of key concepts included in the curriculum at 11–14; the number of schools we were able to work with was limited as some were teaching topics that were still under development at the time of the study.

The BEST resources had an impact on teachers' classroom practice. The teacher notes included in the resources enabled teachers to plan lessons with an increased awareness of research evidence on children's ideas in science, and the diagnostic and response items enabled teachers to gain evidence during lessons about what their students understood and, crucially, why. The extent to which they promoted metacognition and self-regulation depended on how they were used. While the items, particularly confidence grids and talking heads, were designed to promote metacognitive talk, and teachers were observed asking who has the correct and incorrect ideas and their reasons for that, we did not observe teachers asking students to distinguish between opinions and evidence, nor between data and explanations. This is an area where there is further opportunity for the BEST resources to be used.

We observed BEST items being used consistently to identify preconceptions and as a basis for structured feedback to develop students' conceptual understanding. We also saw this being linked to memory, with teachers asking students to recall ideas from previous lessons or topics and to make connections with the idea being taught. Varying degrees of teacher responsiveness were observed – where teachers asked for students' answers in the moment or promoted metacognitive talk, it allowed them to incorporate students' ideas into their teaching, making for more meaningful classroom interactions and formative use of the evidence of students' thinking.

The study suggests that the BEST resources are one way for teachers of science at 11–14 (key stage 3) to access, engage with and use research evidence in science teaching. Teacher notes and learning progressions can inform teachers about more and less effective ways of structuring and introducing science content, and the diagnostic and response items can be integrated into existing lessons or schemes of work.

Our findings indicate that the research summaries provided in the teacher notes can act as research-informed, subject-specific just-in-time professional development. Further work is needed to investigate whether the resources are used over a longer period of time, and whether they affect student outcomes.

BEST is available online at no cost to teachers at www.stem.org.uk/best-evidence-science-teaching. Follow BEST on *Twitter* @BestEvSciTeach for project updates.

Acknowledgements

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The resources have been developed by the University of York Science Education Group in collaboration with science teachers and are available online at no cost to teachers or schools in collaboration with STEM Learning. We are grateful for the support of teachers during the development, review and testing phases of the project. All Best Evidence Science Teaching (BEST) resources are © University of York Science Education Group. The resources are distributed under a Creative Commons Attribution-NonCommercial (CC BY-NC) licence.

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